Phosphorus recovery in municipal wastewater and socioeconomic impacts in Canada and the United States

Edgar Martín-Hernández[a,b,*], Sidney Omelon[b], Céline Vaneeckhaute[a,c], Gerardo J. Ruiz-Mercado[d,e]

[a]*BioEngine - Research Team on Green Process Engineering and Biorefineries, Chemical Engineering Department, Université Laval, 1065 Ave. de la Médecine, Québec, QC, G1V 0A6, Canada*
[b]*Department of Mining and Materials Engineering, McGill University, Montréal, QC H3A 0C5, Canada*
[c]*CentrEau, Centre de recherche sur l'eau, Université Laval, 1065 Avenue de la Médecine, Québec, QC, G1V 0A6, Canada*
[d]*Center for Environmental Solutions and Emergency Response (CESER), US Environmental Protection Agency, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, United States*
[e]*Chemical Engineering Graduate Program, Universidad del Atlántico, Puerto Colombia 080007, Colombia*

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*Corresponding author
Email address: edgar.martinhernandez@mcgill.ca (Edgar Martín-Hernández)

S1. United States Census Divisions

Census Divisions provide territorial divisions similar in terms of development, demographic characteristics, and economic activities [1], being extensively used for the the collection and analysis of data throughout the U.S. [2]. Table 1S collects the states included in each Census Regions and Divisions.

Table 1S: U.S. Census Regions and Divisions.

Census Region	Census Division	States included
Region 1: Northeast	Division 1: New England	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont
Region 1: Northeast	Division 2: Middle Atlantic	New Jersey, New York, Pennsylvania
Region 2: Midwest	Division 3: East North Central	Illinois, Indiana, Michigan, Ohio, Wisconsin
Region 2: Midwest	Division 4: West North Central	Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South Dakota
Region 3: South	Division 5: South Atlantic	Delaware, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, Washington D.C., West Virginia
Region 3: South	Division 6: East South Central	Alabama, Kentucky, Mississippi, Tennessee
Region 3: South	Division 7: West South Central	Arkansas, Louisiana, Oklahoma, Texas
Region 4: West	Division 8: Mountain	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
Region 4: West	Division 9: Pacific	Alaska, California, Hawaii, Oregon, Washington

S2. Demographics and characteristics of the WWTPs/WRRFs assessed

Population in Canada and the United States is unevenly distributed across both countries. In Canada, the population is concentrated in the south of the country, where most of the agricultural lands and urban centers are located. The population density is particularly high in the Quebec City-Windsor corridor, comprising from Lake Erie to the north of the St. Lawrence river. In the case of the United States, the population is concentrated in the coastal areas, the Great Lakes area, and some major cities in the hinterland, while the counties between the Great Plains and the Pacific coast (i.e., the west-half of the hinterland territory) are much less populated even though their comparatively larger size.

The average size of the WRRFs is directly related to the distribution of the population resulting in larger capacities in the more populated regions, as shown in Figure 1S. Additionally, comparing the average size of WRRFs (Figure 1S) and their treatment level (Figure 2 of the manuscript), we observe a predominancy of WRRFs with more advanced treatments in most of the more populated areas except for the Pacific region of the United States, which is a region that shows a predominancy of medium and large-scale facilities with secondary treatment level.

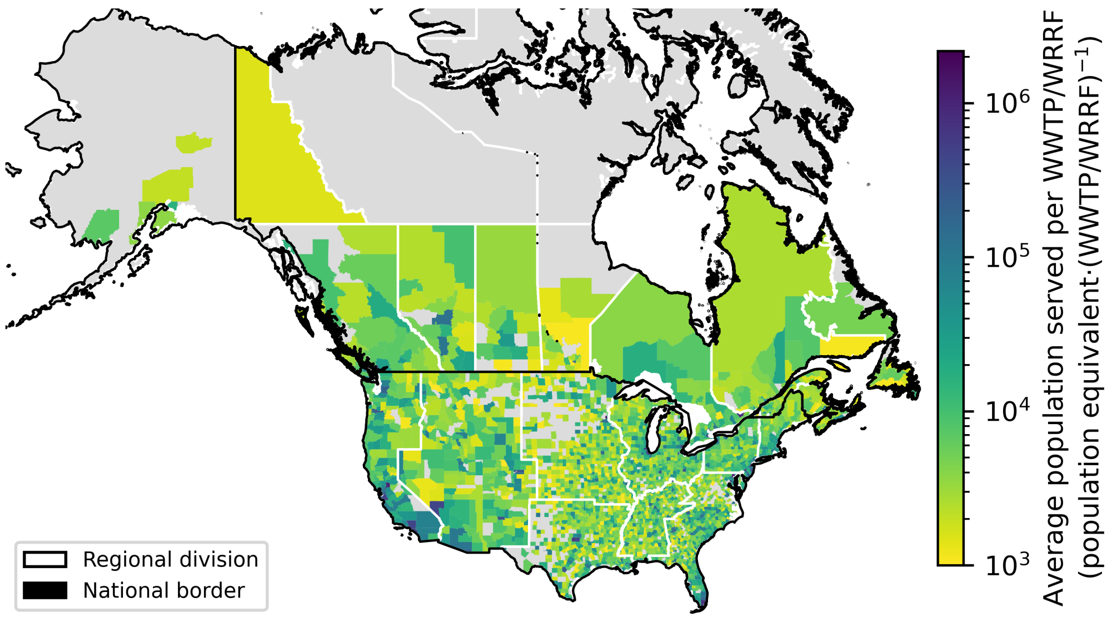
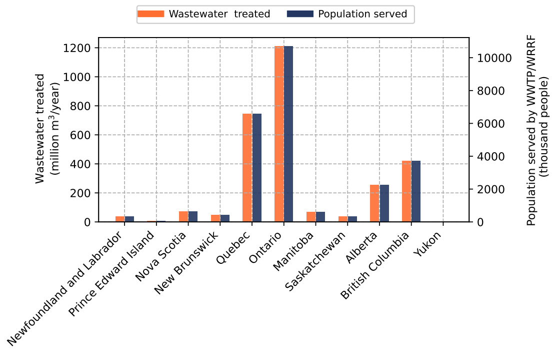


Figure 1S: Average size of the assessed WRRFs in Canada the United States at census division and county respectively..

The distribution of the total population served and wastewater treated by the WWTPs/WRRFs assessed at the regional level (Canadian provinces and U.S. census divisions) can be observed in Figure 2S. 1,039 and 9,219 WWTPs/WRRFs reported in HydroWASTE are assessed for Canada and the United States respectively, serving 25,707,773 and 255,589,818 people which cover the 67.8% and 77.1% of the population living in the targeted regions of Canada and the United States respectively, considering the 2020 population estimates [3, 4].



(a) Canada.

(b) United States.

Figure 2S: Distribution of the total population served and wastewater treated by the WWTPs/WRRFs assessed at the regional level.

S3. Phosphorus recovery costs

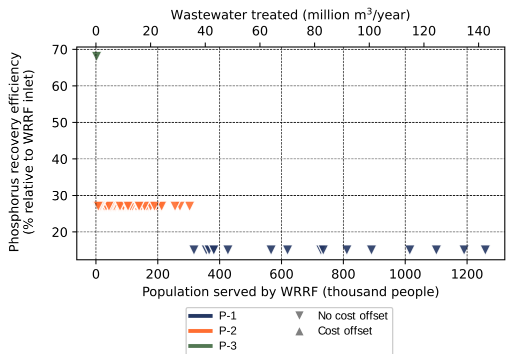
Table 2S: scaling factors and the reference cost-to-capacity values of the assessed phosphorus recovery processes.

Recovery point	Phosphorus recovery system	Treatment capacity$_{Ref}$ (kg P_{inflow}/year)	Annual cost$_{Ref}$ (2022 USD/year)	Scaling factor
Digestate aqueous phase	Precipitation in cylindrical fluidized-bed reactor	65,700	460,715	0.594
	Precipitation in conical fluidized-bed reactor	65,700	197,069	0.364
	Precipitation in semi-continuous stirred reactor	65,700	114,456	0.779
	Precipitation in airlift reactor	65,700	111,745	0.384
	Precipitation in semi-continuous stirred reactor with pre-acidification	65,700	281,622	0.427
Sewage sludge	Wet chemical leaching with heavy metals masking using citric acid	65,700	876,492	0.886
	Wet chemical leaching with heavy metals separation as sulfides	65,700	602,400	0.817
	Wet oxidation followed by nanofiltration	65,700	1,343,352	0.844
	Super critical water oxidation	65,700	1,415,640	0.822
	Metallurgical melting gasification of biosolids	657,000	7,108,320	0.983
Sewage sludge ash	Ash leaching with phosphoric acid	1,150,000	10,346,220	1.000
	Ash thermochemical treatment and chlorination	1,150,000	3,027,060	1.000
	Ash thermochemical treatment with sodium sulfate	1,150,000	3,237,900	1.000
	Ash thermochemical treatment with phosphorus separation in the gas phase	1,150,000	7,891,440	1.000
	Ash thermal treatment and chlorination	1,150,000	32,830,800	1.000

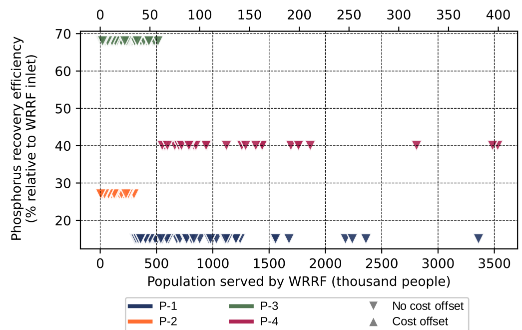
The CAPEX and OPEX are estimated for each recovery process are estimated using the economic data reported by previous studies [5]. The effect of the economies of scale in the cost of phosphorus recovery is assessed through the cost-to-capacity method [6], as shown in Equation 1S. The scaling factors for the different recovery processes (n) are estimated based on the economic information reported for different scales in previous studies [5]. The scaling factors and the reference cost-to-capacity values (Treatment capacity$_{Ref}$ and Annual cost$_{Ref}$) are collected in Table 2S. For the case of processes for phosphorus recovery from sewage sludge ash, the cost of installing and operating an incinerator unit is added to the cost of phosphorus recovery, which assumed value is 12.05 2022 USD/kg P recovered [5].

$$\text{Annual cost}\left(\frac{\text{USD}}{\text{year}}\right) = \text{Annual cost}_{Ref}\left(\frac{\text{USD}}{\text{year}}\right) \cdot \left(\frac{\text{Treatment capacity}\left(\frac{\text{kg P}_{\text{inflow}}}{\text{year}}\right)}{\text{Treatment capacity}_{Ref}\left(\frac{\text{kg P}_{\text{inflow}}}{\text{year}}\right)}\right)^{n} \quad (1S)$$

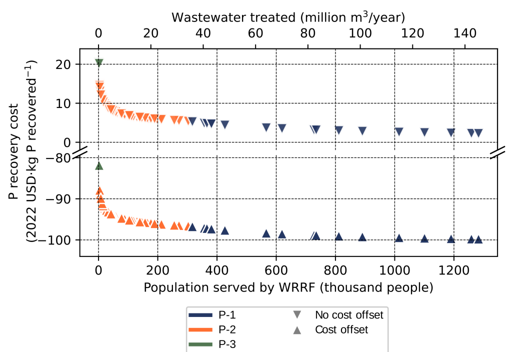
S4. Phosphorus recovery processes selected



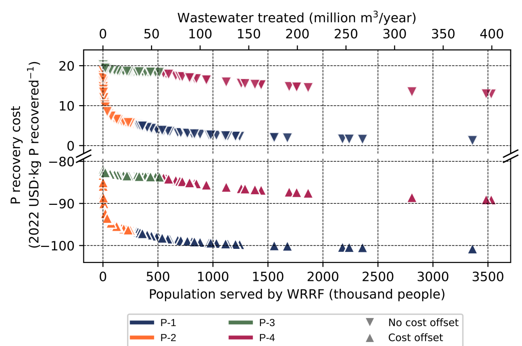
(a) Phosphorus recovery efficiency, Canada.



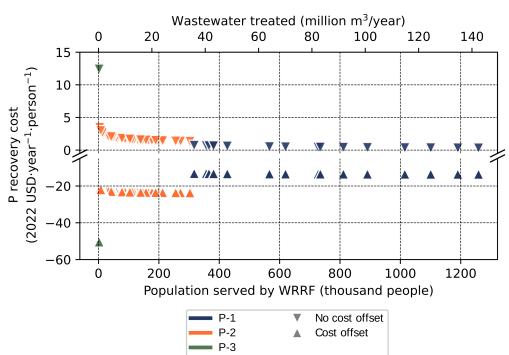
(b) Phosphorus recovery efficiency, United States.



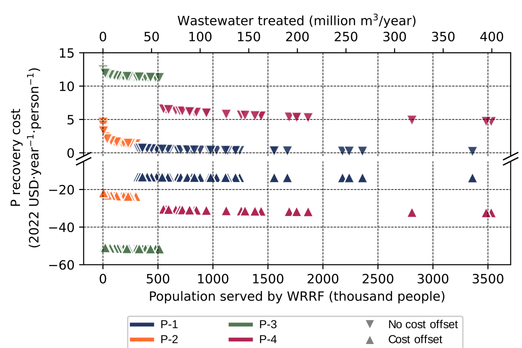
(c) Phosphorus recovery cost, Canada.



(d) Phosphorus recovery cost, United States.



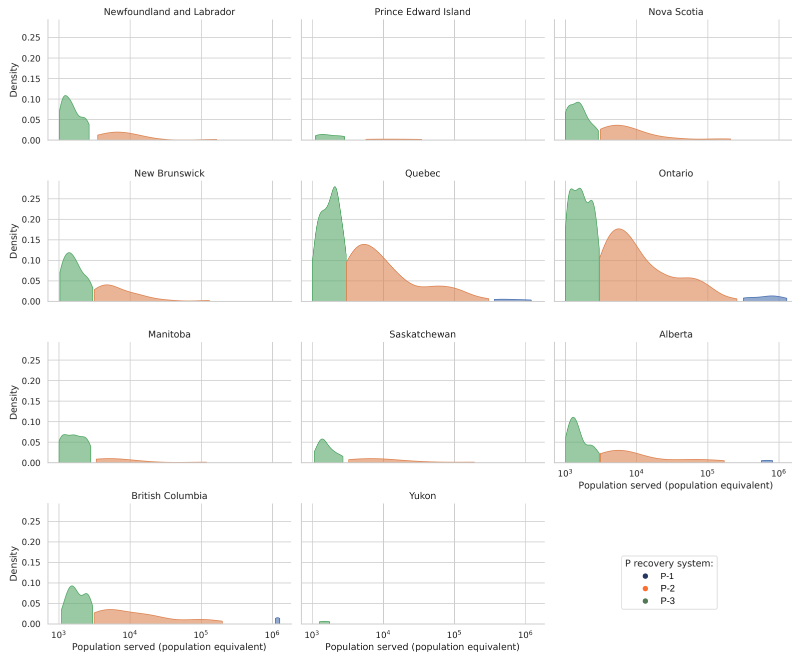
(e) Annual per capita cost of phosphorus recovery, Canada.



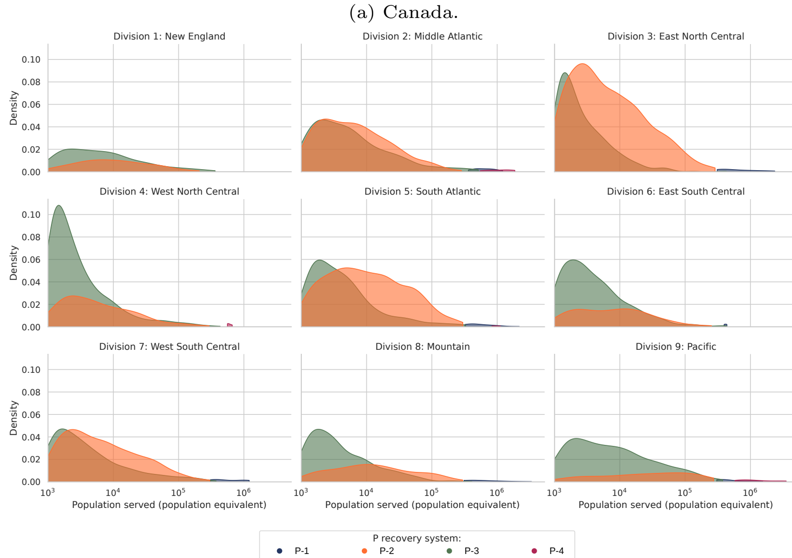
(f) Annual per capita cost of phosphorus recovery, United States.

Figure 3S: Phosphorus recovery processes selected at each WRRF assessed. Y-axis are at different scale to magnify the effect of the WRRF scale in the cost of phosphorus recovery. P-1: Precipitation in airlift reactor; P-2: Precipitation in semi-continuous stirred reactor; P-3: Metallurgical melting gasification of biosolids; P-4: Wet chemical leaching with heavy metals separation as sulfides.

Figure 3S show the phosphorus recovery processes selected at each WRRF assessed together with their recovery efficiency and recovery costs. It can be observed that while for the case of the Canada three different processes are selected, two for phosphorus recovery from the digestate aqueous phase P-1 (precipitation in airlift reactor and precipitation in semi-continuous stirred reactor, denoted as P-1 and P-2 respectively) and one for phosphorus recovery from sewage sludge (metallurgical melting gasification of biosolids, denoted as P-3), for the case of the United States the wet chemical leaching with heavy metals separation as sulfides process (denoted as P-4) for the recovery of phosphorus from sewage sludge is also selected. Since the selection of the phosphorus recovery process considered for each WRRF is based on the most cost-efficient process in terms of cost per mass unit of phosphorus recovered, it can be observed how the economies of scale affect the performance of the different recovery processes. For phosphorus recovery from the digestate aqueous phase at facilities serving under 300,000 population equivalents, P-2 is the most-cost efficient process, while for larger WRRFs the process selected is P-1. Regarding phosphorus recovery from sewage sludge, P-3 is the most cost-effective process for facilities serving under 500,000 population equivalents, while P-4 is the most efficient recovery system for larger WRRFs. None of the assessed cases selected phosphorus recovery from sewage sludge ashes. The density distribution of the selected phosphorus recovery as a function of the WRRF scale at regional level is shown in Figure 4S.



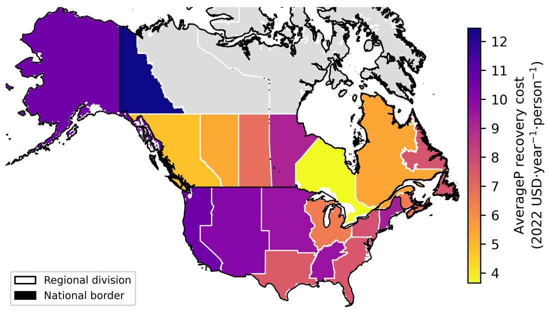
(a) Canada.



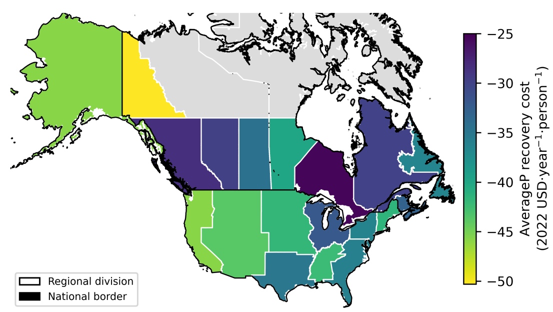
(b) United States.

Figure 4S: Distribution of selected recovery processes as a function of the WRRF scale in the studied regions of Canada and the United States. P-1: Precipitation in airlift reactor; P-2: Precipitation in semi-continuous stirred reactor; P-3: Metallurgical melting gasification of biosolids; P-4: Wet chemical leaching with heavy metals separation as sulfides.

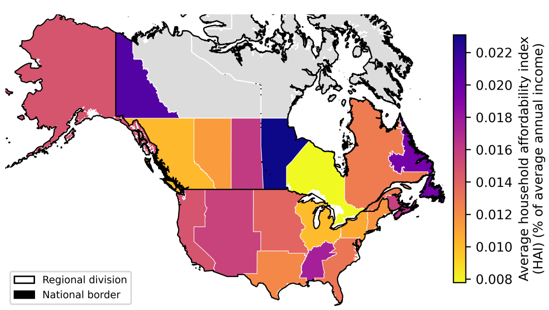
S5. Economic impacts of phosphorus recovery: regional analysis



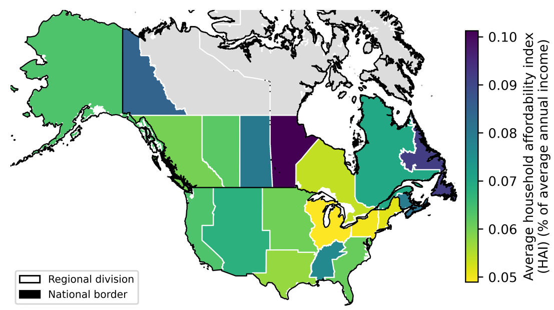
(a) Annual per capita costs of phosphorus recovery excluding the offset cost derived from avoiding potential environmental damage caused by phosphorus releases.



(b) Annual per capita savings due to phosphorus recovery considering the economic offset cost derived from avoiding potential environmental damage caused by phosphorus releases.



(c) Household affordability index of phosphorus recovery excluding the offset of the costs caused by the damages associated with the phosphorus releases.



(d) Savings in terms of household affordability index due to phosphorus recovery considering the economic offset cost derived from avoiding potential environmental damage caused by phosphorus releases.

Figure 5S: Spatial distribution of the annual per capita costs of phosphorus recovery and HAI at province (Canada) and census division (United States) levels when excluding ((a) and (c)) and including ((b) and (d)) the offset cost derived from avoiding potential environmental damage caused by phosphorus releases. No data was available for the regions colored in grey.

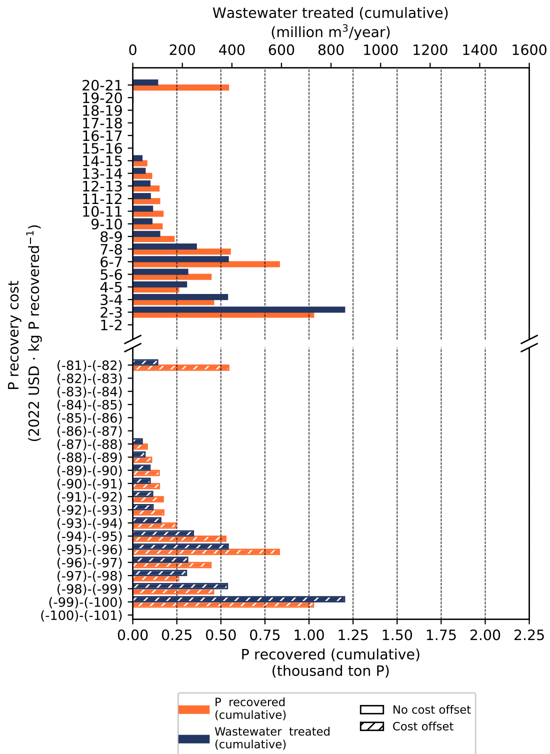
Figure 5S shows the spatial distribution of the annual per capita costs of phosphorus recovery and HAI at province (Canada) and census division (United States) levels when excluding and including the offset cost derived from avoiding potential environmental damage caused by phosphorus releases. In Canada, the lowest phosphorus recovery costs and annual phosphorus recovery cost per capita are observed for the provinces of Quebec, Ontario, Alberta, and British Columbia, while the provinces of Newfoundland and Labrador and Manitoba show the highest costs. In terms of the HAI of phosphorus recovery, Manitoba scores the largest value among the Canadian territories. In the

United States, the lowest phosphorus recovery costs and annual phosphorus recovery costs are observed for the Middle Atlantic, East North Central, South Atlantic, and West South Central census divisions. These lowest phosphorus recovery costs are mainly driven by the large share of facilities with advanced treatment since the average size of the WRRFs in some of these regions is relatively small. The highest phosphorus recovery costs are observed in the West North Central and East South Central census divisions. In terms of the HAI of phosphorus recovery, it can be observed that it follows similar trend than the phosphorus recovery costs.

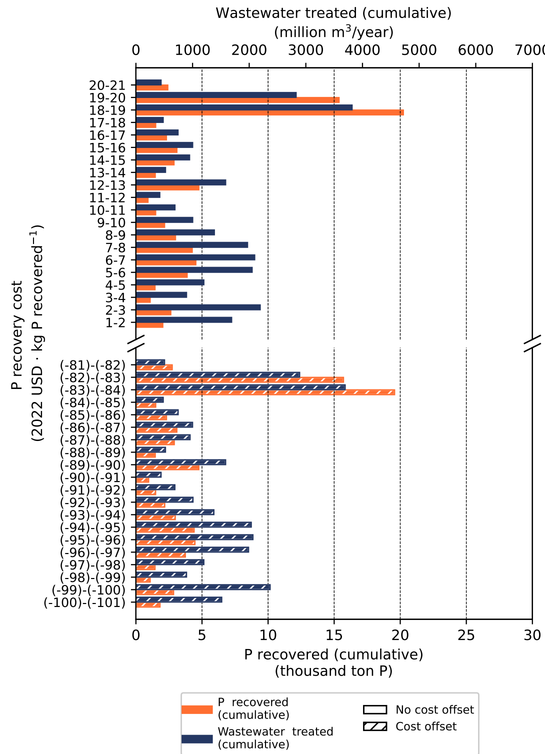
S6. Economic impacts of phosphorus recovery: national level analysis

Figure 6S shows the distribution of cumulative wastewater treated though the phosphorus recovery costs and per capita phosphorus recovery costs. In the case of Canada, it can be observed that a significant fraction of the total wastewater treated results in low phosphorus recovery costs. This is due to the predominancy of WRRFs categorized as advanced in HydroWASTE for Canada, which results in the more cost-effective phosphorus recovery from digestate dewatering effluents instead of from sewage sludge dewatering effluents, as discussed in Section **??**. It can also be observed that a non-negligible fraction of phosphorus is recovered using systems targeting sewage sludge dewatering effluent, which result in larger recovery costs of 20-21 USD per kg of phosphorus recovered. However, it should be noted that due to the higher efficiency of these systems, the phosphorus recovery in relation with the water treated in these systems is significantly larger. The use of phosphorus recovery from sewage sludge dewatering effluents is more important in the United States due to the larger number of WRRFs categorized as secondary treatment level, which contrarily to the case of Canada, results in important amounts of phosphorus recovered at large costs. A similar behavior is observed when the offset of the economic damages by the phosphorus releases avoided is considered, since the high phosphorus recovery costs result in lower economic savings in terms of savings per kilogram of phosphorus recovered.

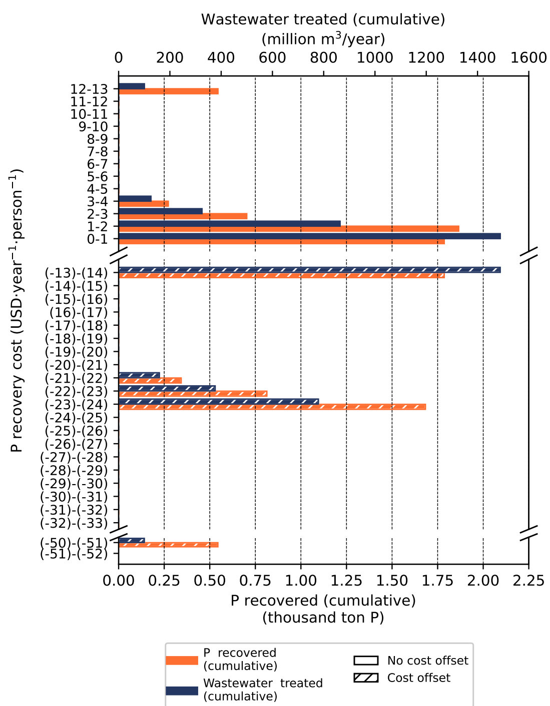
The trend observed in terms of annual per capita phosphorus recovery, shown in Figures 6Sc and 6Sd, is similar if the offset of the economic damages by the phosphorus releases avoided is excluded. However, similarly to the results discussed in Section **??**, when the effect of this offset is considered, the effect of the economies of scale results in larger per capita savings for the communities served by small-scale WRRFs, which is particularly relevant in the case of the United States. This pattern raise might promote the search of specific phosphorus recovery processes for small-scale facilities able to reduce the cost of phosphorus recovery in these WRRFs, since they treat a large fraction of wastewater, and therefore a large fraction of phosphorus in wastewater is processed by them. Alternatively, incentive schemes can be proposed to reduce the gap of phosphorus recovery cost between large and small-scale facilities in order to avoid the emergence of deprived social groups as a consequence of implementing phosphorous recovery systems.



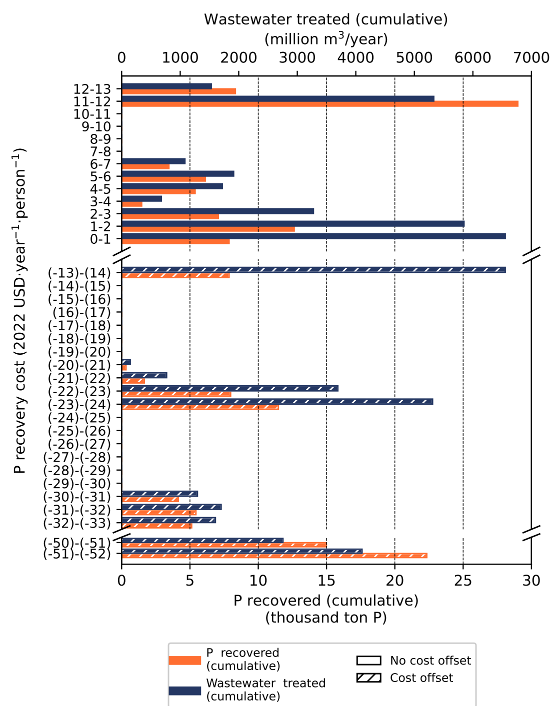
(a) Phosphorus recovery cost, Canada.



(b) Phosphorus recovery cost, United States.



(c) Annual per capita cost of phosphorus recovery, Canada.



(d) Annual per capita cost of phosphorus recovery, United States.

Figure 6S: Distribution of the phosphorus recovery costs at national level.

S7. Feature importance analysis for the household affordability index (HAI)

Table 3S collects the results of the feature importance analyses performed for the household affordability index (HAI).

Table 3S: Feature importance analyses for the household affordability index (HAI).

	Generalized Linear Squares	Random forest
Average population served per WWTP/WRRF	-0.12000	0.47457
Average annual income per capita	-0.37892	0.52543

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